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SOME LIMITS DUE TO RESTRICTIONS ON ENTRY RANGE AND LANDING LIGHTING CONDITIONS

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SUMMARY

Trajectories suitable for Apollo-type lunar missions must satisfy a large variety of constraints. This paper is concerned with two possible constraints for the return phase of the mission; namely, trajectories which (1) require entry ranges less than 5,000 nautical miles, and (2) permit landing within a 4-hour period following sunrise. The general characteristics of trajectories which satisfy these constraints are discussed, and those combinations of lunar launch time, orbital plane inclination, and landing site latitude which allow such trajectories are indicated.

INTRODUCTION

The variety of lunar trajectories is virtually limitless but those of interest in Apollo-type missions must satisfy constraints imposed by various phases of the mission. A current problem in the analysis of lunar trajectories is therefore to indicate those trajectories which satisfy such constraints.

This paper is concerned with the determination of return trajectories which satisfy two constraints that may be imposed by the return phase of the mission; namely, trajectories which (1) require only moderate entry ranges and (2) permit landing during a short period after sunrise. For the quantitative purposes of this work, entry range has been limited to 5000 nautical miles and the landing time has been required to fall within a 4-hour period following sunrise at the landing site. These values represent moderate entry range capability and allow a long period of daylight for any necessary post-landing operations.

A general discussion of entry range requirements is given in references 1, 2, and 3, and some pertinent conclusions of the reference material are reviewed in the first section of this paper. The second section contains an analysis of trajectories which satisfy the constraints on both entry range and landing lighting conditions. The analysis is based largely on two-body orbital considerations and consequently the mathematics of computing return trajectories has been omitted. Reference may be made to references 1 and 3 where this matter has already been covered.

Consider the simple example of return trajectories in the Moon's orbital plane. For a dawn arrival, the landing point is fixed relative to the sun and, assuming some nominal value of the total geocentric angle from the Moon at launch to the landing point at arrival, the phase of the Moon at the time of launch is also fixed. It is expected, therefore, that the main result of any constraint on entry range and arrival times will be a restriction on the period of time each month suitable for launch from the Moon, and the object of this study is an analysis of the periods available in the general three-dimensional problem under the constraints stated above.

SYMBOLS

A_Z	azimuth, measured from north
D	declination or latitude
I	orbital plane inclination angle
RA	right ascension, measured from the vernal equinox
T	time, measured in days from 0 hr, 31 December 1965, Greenwich mean solar time
φ	entry range angle
ξ	geocentric in-plane angle from an ascending node
$(\ )_L$	parameters at landing
$(\ )_M$	parameters at launch from the Moon
$(\ )_S$	solar parameters
$(\ )_{SR}$	parameters at sunrise

TRAJECTORIES WHICH MEET CONSTRAINTS ON ENTRY RANGE

The required range from the point of atmosphere entry to a specified landing site on the Earth depends on (1) the landing site latitude, (2) inclination of the plane of the trajectory returning from the Moon, and (3) declination of the Moon at the time of launch. Thus entry range depends primarily on purely geometric parameters. The desired longitude at landing has only a second-order influence and will be neglected herein. An analysis of the effects of all the parameters in a complete two-body investigation of entry range is given in reference 3; here only the major trends are reviewed with the aid of figures 1 and 2.

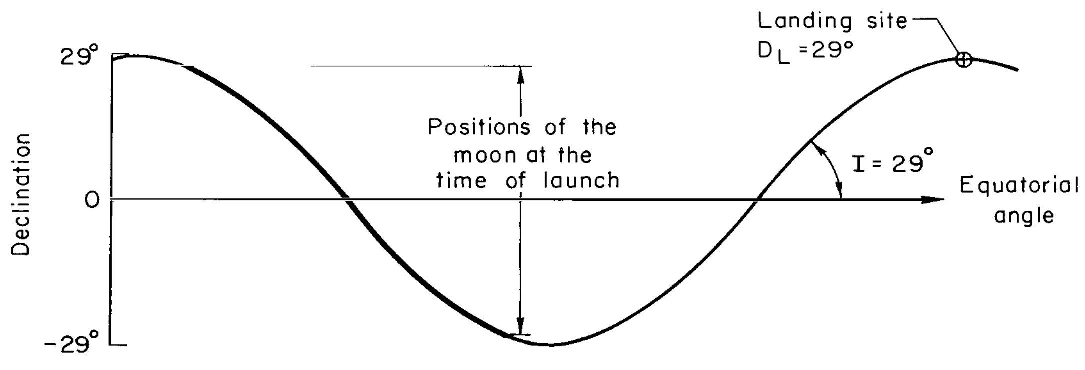
Figures 1(a) and 1(b) give the approximate entry range for trajectories returning to landing sites at latitudes 29° (San Antonio, Texas) and -31.4° (Woomera, Australia). These plots are typical for sites in the Southwest United States and Southern Australia, respectively.

The approximate entry range is computed as follows: the total geocentric angle from the Moon at launch to the landing site is computed from the geometric parameters mentioned above (cf. ref. 3). This angle is composed of the true anomaly of the orbital phase of the trajectory from launch to vacuum perigee and the angle from vacuum perigee to landing. A nominal value of 172° has been assigned to true anomaly, which corresponds roughly to a flight time of three days when the Moon is at its mean distance from the Earth. Entry is defined as that point on the trajectory which has an altitude of 400,000 feet; in this case the geocentric angle from entry to vacuum perigee is very nearly 12° for all trajectories in the range of interest and the range angle from entry to landing is then:

$$\varphi = \xi_L - \xi_M - 160^\circ$$

where $\xi_L - \xi_M$ is the total geocentric angle from launch to landing. For a given time of lunar launch and inclination of the trajectory plane, several trajectories are available which return to a specified landing site. The flight times of the trajectories differ by a sidereal day; that is, a solution of the return trajectory problem is always available with flight time within any 1-day range of values. If the solutions of interest are restricted to those with flight times in the range from 2.5 to 3.5 days, then the nominal value assigned to true anomaly, 172°, is in error by, at most, 5°, for which the corresponding error in the approximate calculation of entry range is 300 nautical miles. This degree of approximation in the data of figures 1 and 2 will be satisfactory for present purposes.

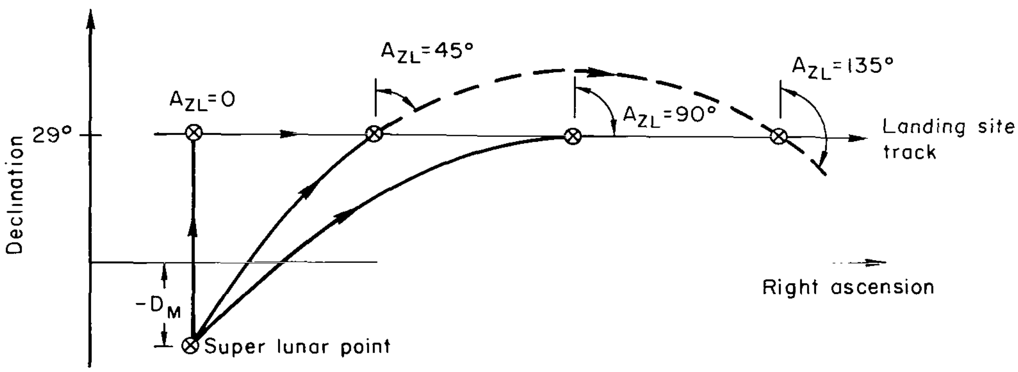
Figure 1(a) illustrates two trends typical of landing sites in the Southwest United States; the required entry range increases with lunar declination, and with landing azimuth. The behavior of entry range with lunar declination may be understood from sketch (a) of the inertial track (declination vs. equatorial angle from an ascending node) of trajectories with an inclination of 29°. The ascending nodes for all such trajectories are superposed in this sketch because the geometric parameters of interest in this discussion are independent of the inertial location of the ascending node.



Sketch (a).- Return orbit tracks, I = 29°.

The landing site is located on the track at 29° latitude. Such orbits correspond to minimum inclination returns to San Antonio ($I = 29°$, $A_{ZL} = 90°$). As the declination of the Moon at launch varies, the Moon will occupy successive positions on the return trajectory track between the maximum and minimum declination of the Moon for the month. It is seen in the sketch that the total in-plane angle from the Moon to the landing site decreases with decreasing lunar declination. This decrease requires an almost equal decrease in the entry range angle, and slight adjustments in true anomaly (hence, flight time) of the orbital portion of the trajectory in order to obtain the correct longitude at landing. The same trend occurs at all values of inclination.[1]

The nature of the dependence of the required entry range on landing azimuth can be seen in the inertial tracks of several return trajectories in sketch (b). The trajectories shown have the same launch time and various values of landing azimuth. The "super lunar point" is taken 180° from the direction of the Moon at the time of launch and hence has a declination of $-D_M$. All trajectories pass through this inertial location. The total in-plane angle from the Moon to landing is then 180° plus the angle from the super lunar point to landing. It is



Sketch (b).- Return orbit tracks for fixed D_M.

readily seen from the sketch that this angle increases with landing azimuth. This increase is taken up by an almost equal increase in the required entry range, and by slight adjustments in the orbital true anomaly in order to obtain the correct longitude at landing.

The requirements for landing at Woomera, Australia ($D_L = -31.4°$) are given in figure 1(b). It is evident here that the trends are opposite to those for landing sites in the Southwest United States, as can be explained by sketches similar to sketches (a) and (b).

Finally, the general restrictions on combinations of landing site latitude, lunar declination, and inclination of the return trajectory plane, which result from a restriction on entry range to 5,000 nautical miles, are given in figure 2. The curves shown in figure 2(a) are lines of constant inclination angle on which

[1]It is also seen from sketch (a) that additional return trajectories exist ad infinitum by extending the track to the right and left and then considering all locations on such a track between the maximum and minimum declination of the Moon. These cases, however, require very large post-entry ranges or retrograde orbital motion and will not be considered in this discussion.

the approximate entry range is 5,000 nautical miles or less. To every point within a constant inclination curve there corresponds a trajectory having the same inclination angle but with an entry range requirement between 1,200 and 5,000 nautical miles (i.e., with a total geocentric angle between 180° and 243°). Thus, all combinations of landing site latitude and lunar declination within the curve may be reached by trajectories of the same inclination with entry ranges under 5,000 nautical miles. If entry range is unrestricted, then the entire rectangular region, $-I \leq D_M, D_L \leq I$, can be reached by trajectories with inclination angle, I. This is illustrated in figure 2(b) for the case $I = 30^\circ$ with curves of constant entry range from 1,200 to 12,000 nautical miles. The region which may be reached with trajectories at an inclination angle of 30° and entry range under 5,000 nautical miles has been shaded in figure 2(b), and this region is the same as that enclosed by the curve for $I = 30^\circ$ in figure 2(a).

In summary, the following conclusions are noted concerning the entry range requirements of trajectories returning from the Moon:

(1) It is possible to return from the Moon to a specified landing site with any desired inclination (greater than the minimum possible value) provided the necessary entry range capability is available. If the entry range capability is limited, then there will be restrictions on the combinations of lunar declination, inclination angle, and landing site latitude which can be used.

(2) The required entry range for landing sites in the Southwest United States increases with increasing declination of the Moon and increasing azimuth at landing. More specifically, figure 1(a) indicates that with San Antonio ($D_L = 29^\circ$) as the landing site, the required entry range is less than 5,000 nautical miles at all times for polar return orbits ($I = 90^\circ$, $A_{ZL} = 0^\circ$). On minimum inclination orbits ($I = 29^\circ$, $A_{ZL} = 90^\circ$) the entry range is less than 5,000 nautical miles for launch from the Moon during that portion of the month when the lunar declination is less than -13° approximately.

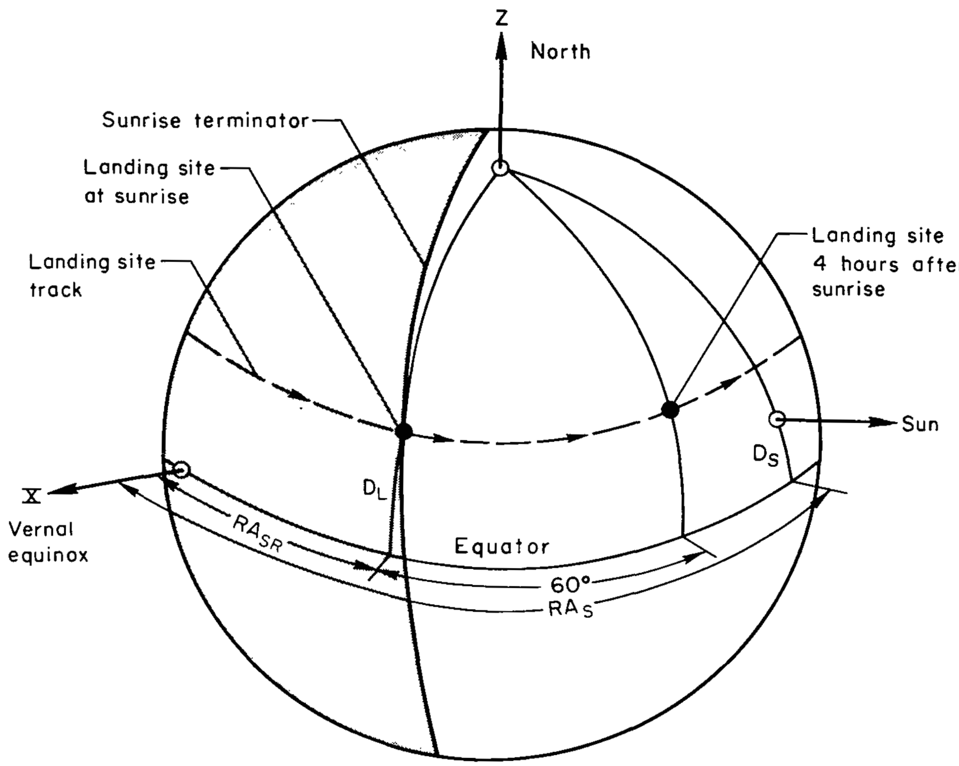
(3) For landing sites in the region of Woomera, Australia ($D_L = -31.4^\circ$), the required entry range decreases with increasing lunar declination and increasing azimuth at landing. In the case of Woomera, the required entry range on polar return orbits ($I = 90^\circ$, $A_{ZL} = 180^\circ$) is under 5,000 nautical miles at all times of the month, and for return orbits of minimum inclination it is under 5,000 nautical miles only for that part of the month when the Moon is at declinations greater than about 14°.

TRAJECTORIES WHICH MEET CONSTRAINTS ON BOTH ENTRY RANGE AND LANDING LIGHTING CONDITIONS

The object of this section is to indicate the characteristics of trajectories returning from the Moon which permit landing within a 4-hour period after sunrise. The period of 4 hours allows a long period of daylight for any necessary search and recovery operations.

General Considerations

Some preliminary facts are of interest; sunrise occurs on the sunrise terminator, at a right ascension which depends both on latitude and the position of the Sun. Sunrise occurs at any particular landing site when it passes through the sunrise terminator, and 4 hours later it will be located at a right ascension 60° in advance of its right ascension at sunrise since the Earth rotates 15° per hour. These facts are illustrated in sketch (c).



Sketch (c).- Celestial sphere.

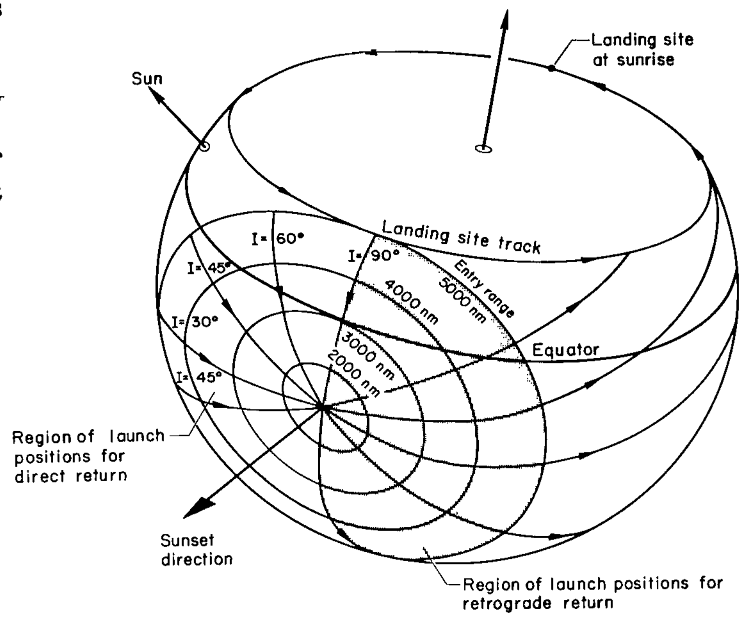
The right ascension of sunrise, RA_{SR}, for any latitude can be computed, given the position of the Sun, from

$$\left.\begin{aligned} \cos(RA_S - RA_{SR}) &= -\tan D_L \tan D_S \\ 0 < RA_S - RA_{SR} &< \pi \end{aligned}\right\} \qquad (1)$$

For return trajectories in the Moon's orbital plane, it may be reasoned that, since the entry range restriction limits the total in-plane angle to values between 180° and 243°, a dawn arrival would place the Moon at the time of launch somewhere between new Moon and first quarter. One of the main results of the restriction on arrival lighting conditions is, therefore, a restriction on the time of launch from the Moon.

To determine the nature of this restriction in the general three-dimensional problem consider, first, the inertial position of some desired landing site at a time of sunrise. In order to land at this inertial location with entry range between 1,200 and 5,000 nautical miles, the total in-plane angle of the return trajectory is between 180° and 243°; therefore, the launch position for such trajectories must be located in a certain region of the sky. This region is contained in a cone of half-angle 63° centered on the "sunset direction" (180° from the direction that the landing site occupies at sunrise). For example, at sunrise, September 23, 1966, San Antonio is located inertially at a right ascension of 82°. The right ascension and declination of the cone axis, or sunset direction, is then 262° and -29°, respectively, and all directions within 63° of this cone axis are possible locations of the launch position for trajectories with a dawn arrival under the entry range limits.

The region of launch positions for a dawn arrival (sketch (d)) corresponds approximately to a landing site at 30° latitude. Only half the region need be considered here since launch positions east of a vertical plane through the sunset direction require retrograde orbital motion. At each point in the region of launch positions, unique values of entry range and inclination angle are required and the region may be mapped for values of these parameters, as illustrated.



Sketch (d).- Celestial sphere - region of launch positions for dawn arrival.

Next, as the landing site occupies successive positions on its inertial track during the 4-hour period after sunrise, the corresponding half-cone of launch positions sweeps out the region of the celestial sphere in which the Moon must be located at the time of launch in order for the return trajectory to meet the constraints on entry range and landing lighting conditions. This is shown in figure 3, where the appropriate region of the sky is denoted by the shaded area and T_{SR} refers to the time of sunrise at the landing site. The shaded area corresponds to a maximum entry range of 3,000 nautical miles (cone half-angle of 30°) and to a landing site at 30° latitude. The number given on each line in the shaded area is the minimum required entry range for launch positions on that line. This region may also be mapped for various parameters describing the return trajectories.

The shaded region of figure 3 is the area of the celestial sphere which must contain the Moon at the time of launch in order to meet the constraints on entry range and landing lighting conditions. This area moves inertially with the Sun; that is, once around the celestial sphere during a year. The Moon is in this region during each synodic month around the time of first quarter, which occurs at the time the Moon passes through the plane of the sunset terminator. For other landing site latitudes, the "sunset direction" and the shaded region of figure 3 are moved together along the sunset terminator. The precise period when the Moon is in the required region of the sky depends in detail on the declination of the Sun, landing site latitude, and the position of first quarter in the lunar orbit. Nevertheless, under suitable restrictions, the effects of these parameters are small and figure 3 serves to illustrate the following general conclusion:

Launch times for which return trajectories land within 4 hours after sunrise, with entry range less than 5,000 nautical miles, is limited to the period of the month just preceding and just following first quarter. For landing sites between $\pm 35^{\circ}$ latitude, this period is of the order of 7 to 10 days and is available during all months.

Finally, it should be noted that the shaded region of figure 3 expands with increased entry range capability; with an entry range of 12,000 nautical miles (total in-plane angle of 360°) the corresponding area, utilizing both direct and retrograde return orbits, covers the entire celestial sphere. Restricted to direct orbits alone, the area covered includes all but a section of about 110° of the Moon's orbit, which may also be included by raising the post-entry range capability to about 19,000 nautical miles. Thus, the restriction to launch during the period of the month near first quarter in order to meet the constraints on lighting conditions at landing results mainly from the restriction on entry range capability.

Trajectories to Specific Landing Sites

The preceding discussion indicated the existence of a restriction on the period of the month suitable for return from the Moon under the assumed constraints on entry range and landing lighting conditions. The following analysis will give specific examples, for which the appropriate period of the month is computed more precisely and will discuss the effects of restriction to specified values of inclination of the return trajectory. To explore the requirements in the case of land-based landing areas, computations were made for sites at latitudes 29° (San Antonio) and -31.4° (Woomera) for the year 1966. The results noted are typical of sites in the Southwest United States and Southern Australia.

Available periods of launch from the Moon.- The precise period during which suitable return trajectories are available depends on the many details in the problem; one method for rapidly determining this period in specific cases is to plot the position of the Moon across the required region of the celestial sphere indicated in figure 3. This region can be mapped for entry range requirements as previously discussed and two such maps, for landing sites at 29° and -31.4°, are given in figures 4(a) and (b). In both cases the mapping of entry range limit lines for the region near the poles, outside the range of lunar declination, has been omitted. The coordinate along the abscissa of figures 4(a) and (b) is right ascension relative to the "sunset direction" at the time of landing, where the sunset direction is located inertially at declination $-D_L$, and at a right ascension 180° in advance of sunrise at the time of landing, $RA_{SR}(D_L,T_L) + 180^{\circ}$. The right ascension, $RA_{SR}(D_L,T_L)$, is computed from equation (1).

The track of the Moon relative to the maps of figures 4(a) and (b) is computed as follows: For any specified time of leaving the Moon, T_M, the Moon's inertial direction, $D_M(T_M)$, $RA_M(T_M)$, is obtained and the coordinates of the Moon in figure 4(a) are then $(RA_M(T_M) - RA_{SR}(D_L, T_M + 3) - 180^\circ)$ along the abscissa and $D_M(T_M)$ on the ordinate. Here, the time of landing has been approximated as three days after the time of leaving the Moon.

Figures 4(a) and (b) show the Moon's track across the required region of the sky near the times of first quarter in March, June, and September of 1966 for landing sites at Woomera and San Antonio. In each case, the Moon's track is marked off in 1-day intervals, with the date given in days from 0 hr, 31 December 1965, Greenwich mean time. The location of first quarter is also given. For the cases shown, the length of time spent by the Moon in the required region varies from 7 to 10 days. For any particular month the available period varies somewhat with landing site latitude, but, for landing sites between the latitudes of San Antonio and Woomera, the available period each month will be in the same range, from 7 to 10 days. For sites at latitudes substantially above San Antonio or below Woomera, the Moon's track may be located outside the required region for most of the time near first quarter during some months, and the periods available could then be much less than 7 days; for example, a site at latitude 40° N would allow only about 3 days in March 1966.

Inclination angle effects.- Figures 4(a) and (b) establish the available period of launch times without regard for the inclination of the return trajectory. It is of interest to determine the available period for various inclination angles; to do this, the right ascension at landing is computed and compared to the right ascension of sunrise for the landing latitude at the time of landing. The right ascension at landing depends on purely geometric parameters; it is a function of the landing site latitude, inclination of the return trajectory plane (or, equivalently, azimuth at landing), and the position of the Moon at the time of launch. Having specified these parameters, the right ascension at landing is readily computed.[2] Equation (1) is next used to obtain the right ascension of sunrise at the landing site latitude for the time of landing, where the time of landing is taken as 3 days after the time of leaving the Moon. Since return trajectories which adjust for the correct longitude of landing are always available with flight times between 2.5 and 3.5 days and since the sun changes right ascension by about 1° per day, then the 3-day approximation of the return flight time corresponds to an error of at most $1/2^\circ$ in estimating the right ascension of sunrise at the time of landing. The positions of the Sun and Moon have been taken from the Naval Observatory ephemerides in this work.

The results of computations for return to San Antonio during the months of March and September 1966 are given in figures 5(a) and (b). These figures contain curves of right ascension at landing versus time of leaving the Moon for various inclination angles of the return trajectory plane; the curves show only those solutions which correspond to direct orbital motion and have entry ranges less than 10,000 nautical miles. For landing sites in the Southwest United

[2]Methods of computing the right ascension at landing have already been described in reference 3 and elsewhere; for example, equations (2), (3), (4), and (5) of reference 3 may be used directly.

States, this generally restricts consideration to flights arriving from the Southwest. However, the graphs can, in fact, be filled twice over with additional solutions for trajectories requiring large entry range or retrograde motion. Such solutions are omitted from this discussion.

Also shown in figure 5 are two lines giving the right ascension of sunrise and sunrise + 4 hours at the time of landing, where the right ascension of sunrise + 4 hours refers to the right ascension which a point on the Earth's surface at the latitude of landing would have 4 hours after passing through the sunrise terminator. In addition, lines of constant entry range are plotted. These can be obtained, for example, from figure 1 and plots of lunar declination versus time, such as those found in reference 4 for the period 1961 - 1971.

Taken together, the curves in figure 5 indicate the periods of launch time and values of inclination of the return trajectory plane which provide trajectories satisfying the constraints on both entry range and landing lighting conditions. The appropriate ranges of T_M and I are represented in figure 5 by the shaded areas; as expected, the period of suitable launch times is restricted to a portion of the month on the order 7 to 10 days, from about 2 to 5 days before first quarter to 4 to 5 days after first quarter. With a maximum entry range of 5,000 nautical miles and for landing sites between $\pm 35^{\circ}$ latitude, such a period is available during all months if all inclination angles are considered. However, if consideration is restricted to a single value of inclination, the results are more complex.

A comparison of figures 5(a) and (b) for the case of minimum inclination of the return trajectory plane ($I \approx 29^{\circ}$) shows that a 6-day period is available in September 1966, but no period is available in March; that is, minimum inclination trajectories which return to San Antonio and satisfy the desired constraints are not available during some months of the year. This result may be understood as follows.

The right ascension of the Sun varies through 360° during the year, and, consequently, the location of first quarter in the lunar orbit also changes; that is, during some months first quarter occurs when the Moon is at positive declinations and at other times when the Moon is at negative declinations. As noted in the section entitled "Trajectories Which Meet Constraints on Entry Range," return trajectories at minimum inclination with entry ranges less than 5,000 nautical miles are available only when the Moon's declination is below -13°. In that case, there will be months (when first quarter occurs at positive declinations of the Moon) when it is impossible to return on a minimum inclination trajectory with the desired constraints. Such a case is given in figure 5(b) for March 1966, when the lunar declination at first quarter is 27°. A favorable month allowing minimum inclination returns is September (fig. 5(a)). Here, first quarter occurs with the Moon at -27° declination.

It is apparent, then, that most of the months which allow minimum inclination returns to San Antonio under the desired constraints are readily identified as those months for which the lunar declination is below -13° at the time of first quarter. For all of the late 60's this will occur in the Fall and during 1966 the times of first quarter from late August through mid-December are suitable.[3]

As noted in the section entitled "Trajectories Which Meet Constraints on Entry Range," the trends in entry range requirements for return to Southern Australia are reversed from those characterizing landing sites at latitudes of the Southwest United States. Minimum inclination return trajectories to Woomera under the desired constraints should, therefore, be available during those months when none is available for San Antontio. This is illustrated in figure 5(c) for the month of March 1966.

The required entry range on minimum inclination returns to Woomera is under 5,000 nautical miles only for that part of the month when the lunar declination is above 14°. Hence, months for which such trajectories occur and also meet the constraint on landing lighting conditions are those for which the lunar declination is above 14° at the time of first quarter. For all of the late 60's this occurs in the Fall (locally) months; for 1966 the times of first quarter from late February to mid-June are suitable.

For polar orbits returning to either Woomera or San Antonio the required entry range is less than 5,000 nautical miles at all declinations of the Moon and a suitable period of the month is available during every month of the year. This period corresponds to the time that the coordinate of the Moon along the abscissa of figure 4(a) is between 0 and 60°, which is roughly a period of 4-5 days immediately following first quarter.

Effects of landing site latitude.- The discussion of figure 5 indicated that a period of time during which return trajectories are available under the assumed constraints will occur during every month at high values of inclination for landing at either Woomera or San Antonio. However, at low values of inclination ($I \cong 30^{\circ}$) the period available at any landing site varies throughout the year. For example, a landing site in the Southwest United States allows a period of varying length during the Fall months. The addition of Woomera as an alternate site increases the number of months during which returns are possible but several months remain during which the period is low. It is therefore of interest, in the case of low inclination return trajectories, to determine whether the unrestricted choice of one or several landing area latitudes each month will allow a maximum period of launch time. While it is beyond the scope of this work to treat this method of landing site choice extensively, some of the more evident results can be pointed out.

A rapid method of analysis in specific cases is a mapping of the required region of launch positions of figure 3 for inclination of the return trajectory. This type of mapping is illustrated in figure 6 for an equatorial landing site; in order to return with an inclination of 30° to an equatorial landing site under the assumed constraints, the Moon must be located at the time of launch in the shaded region of figure 6. The curved boundaries of this region are formed by the tracks of trajectories at 30° inclination angle which land at the limiting

[3]Rapid determination of those months can be made from plots of lunar declination and phase versus time, such as those in reference 4.

times of sunrise and 4-hours after sunrise, and the remaining two boundaries occur from the 5,000-nautical-mile limit on entry range. In general, the inclination angle map will depend on both inclination angle and landing latitude.

The Moon's track is plotted in figure 6 for every second month of 1966 and is marked off in 1-day intervals. The periods of time that the Moon is in the required region for return trajectories at 30° inclination angle vary from 2 to 7 days and increases to 9 days for several months not shown. For those months when the available period is low, a change in landing area latitude can be used to increase the time allowed for launch; for example, a change in landing latitude to -25° increases the period available in January to 7 days. However, the maximum length of the period of launch times is limited mostly by the restriction in entry range independent of other parameters, and the maximum period that can be obtained by the suitable choice of one or several landing areas each month will be limited to about 10 days.

CONCLUSIONS

The following conclusions are stated for the periods of time during which it is possible to launch from the Moon onto direct return trajectories which require entry ranges less than 5,000 nautical miles and which permit landing during a 4-hour period after sunrise.

1. The period of suitable launch times is restricted to a part of each synodic month just preceding and just following the time of first quarter. For landing sites between ±35° latitude, such a period, on the order of 7 to 10 days, is available during all months, if all inclinations of the return trajectories are considered.

2. The existence of a restriction on launch times results mainly from the restriction on entry range, and the available period will increase with increased entry range capability.

3. The period of suitable launch times is further restricted for specific landing sites if inclination of the return trajectory is restricted to a single value. For landing sites at latitudes of the Southwest United States and Southern Australia, a period of about 4 to 5 days, for polar return trajectories, is available every month immediately following first quarter. In the case of minimum inclination returns to these latitudes, a period is available only during some months of the year; for all of the late 60's, the Fall (locally) months will be suitable. For sites near San Antonio and Woomera, suitable months are characterized as those for which the lunar declination is below -13° and above 14°, respectively, at the time of first quarter.

4. If the return trajectory inclination is restricted to low values ($I \cong 30^{\circ}$) and the landing area latitude may be arbitrarily chosen, then a suitable choice of one or several latitudes can be made each month to allow a period of 7 to 10 days during which returns are possible under the constraints on entry range and landing lighting conditions.

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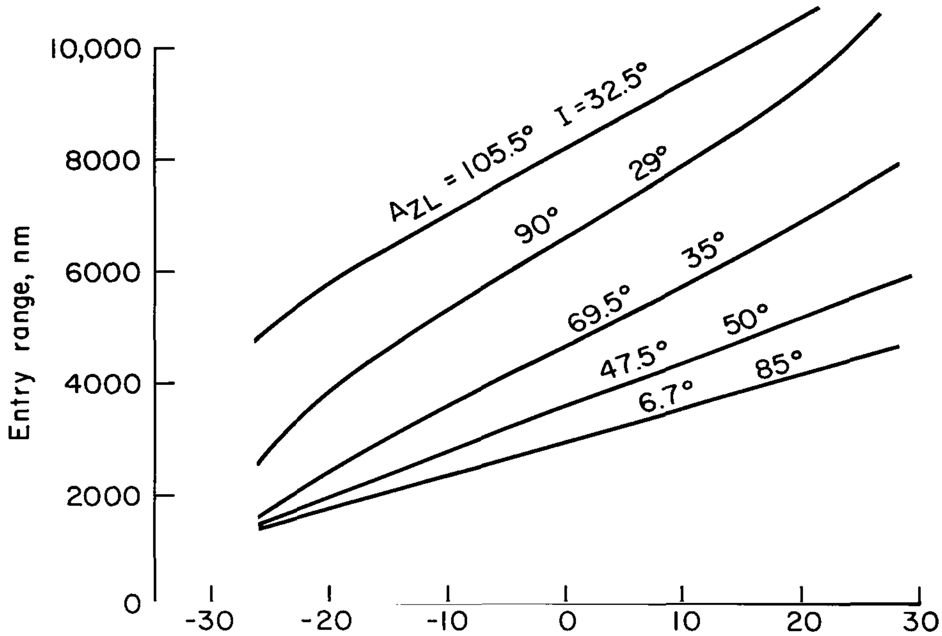
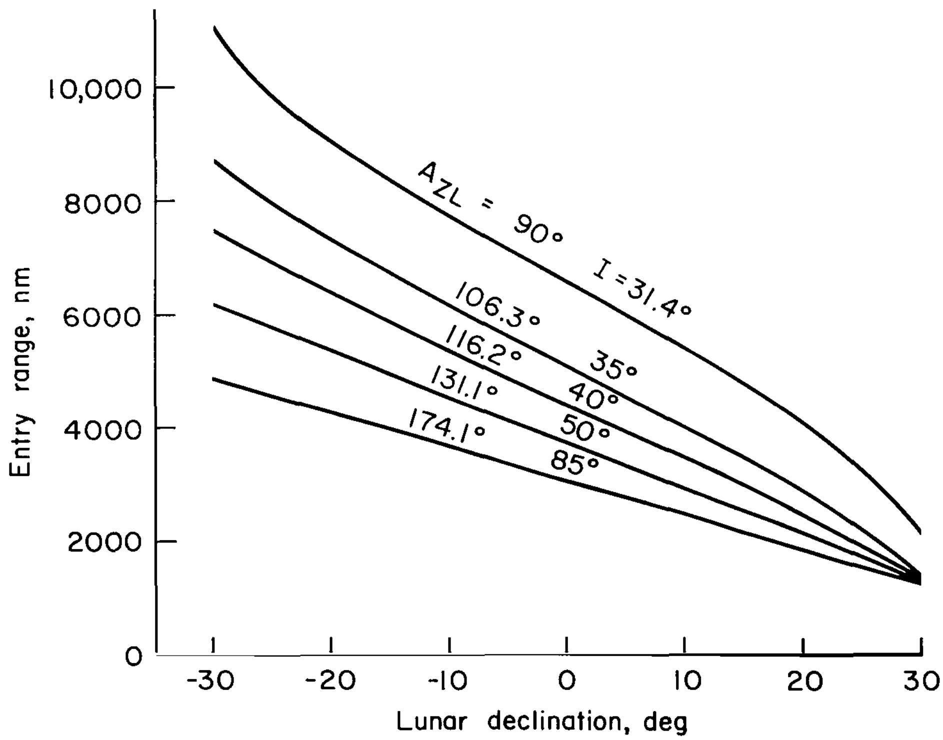
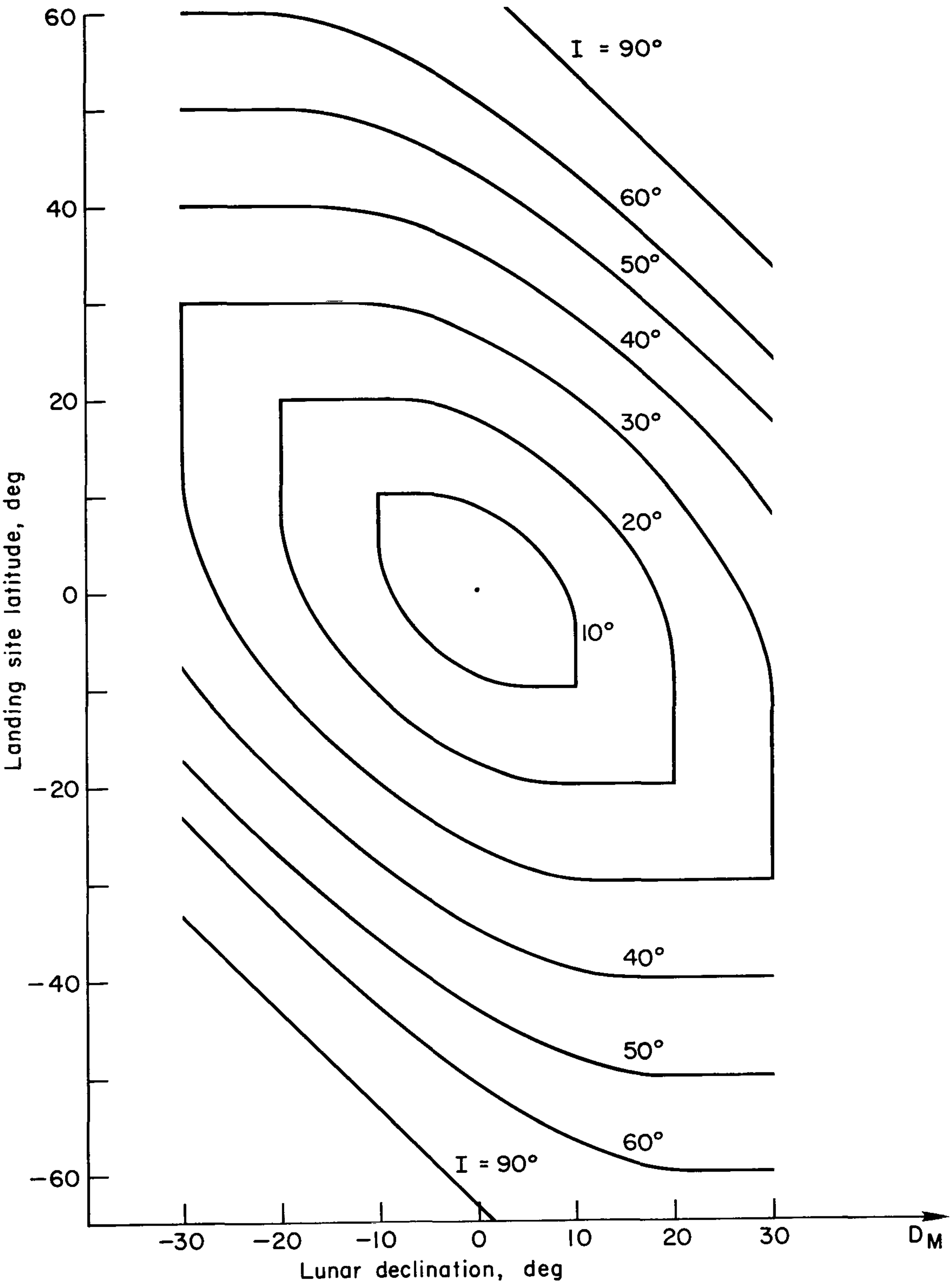


(a) Landing latitude 29°.



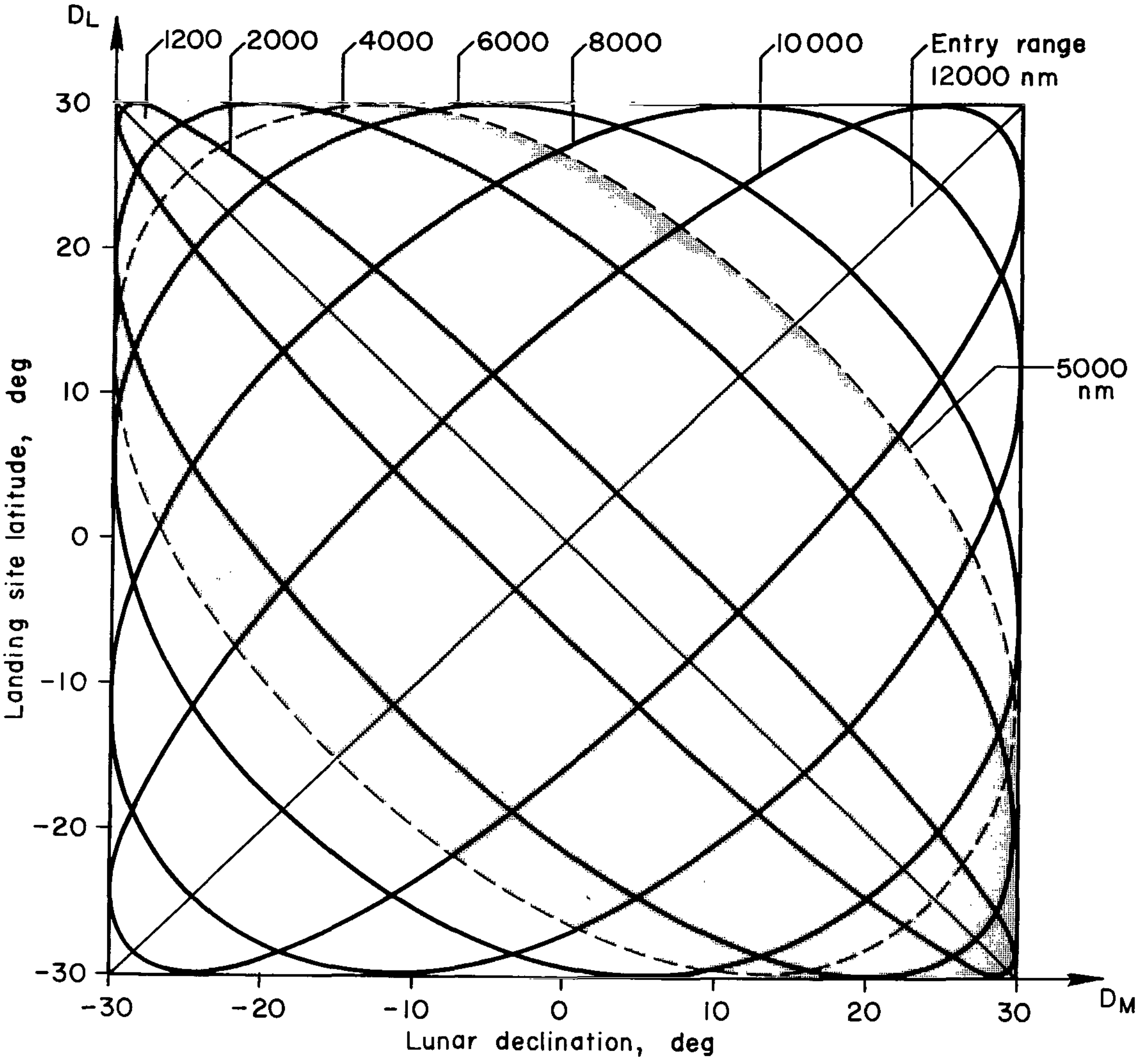
(b) Landing latitude -31.4°.

Figure 1.- Variation of entry range requirements with lunar declination.



(a) Lines of constant inclination angle; entry range ≤ 5000 nm.

Figure 2.- Restrictions imposed on trajectory parameters by restrictions on entry range.



(b) Lines of constant entry range; I = 30°.

Figure 2.- Concluded.

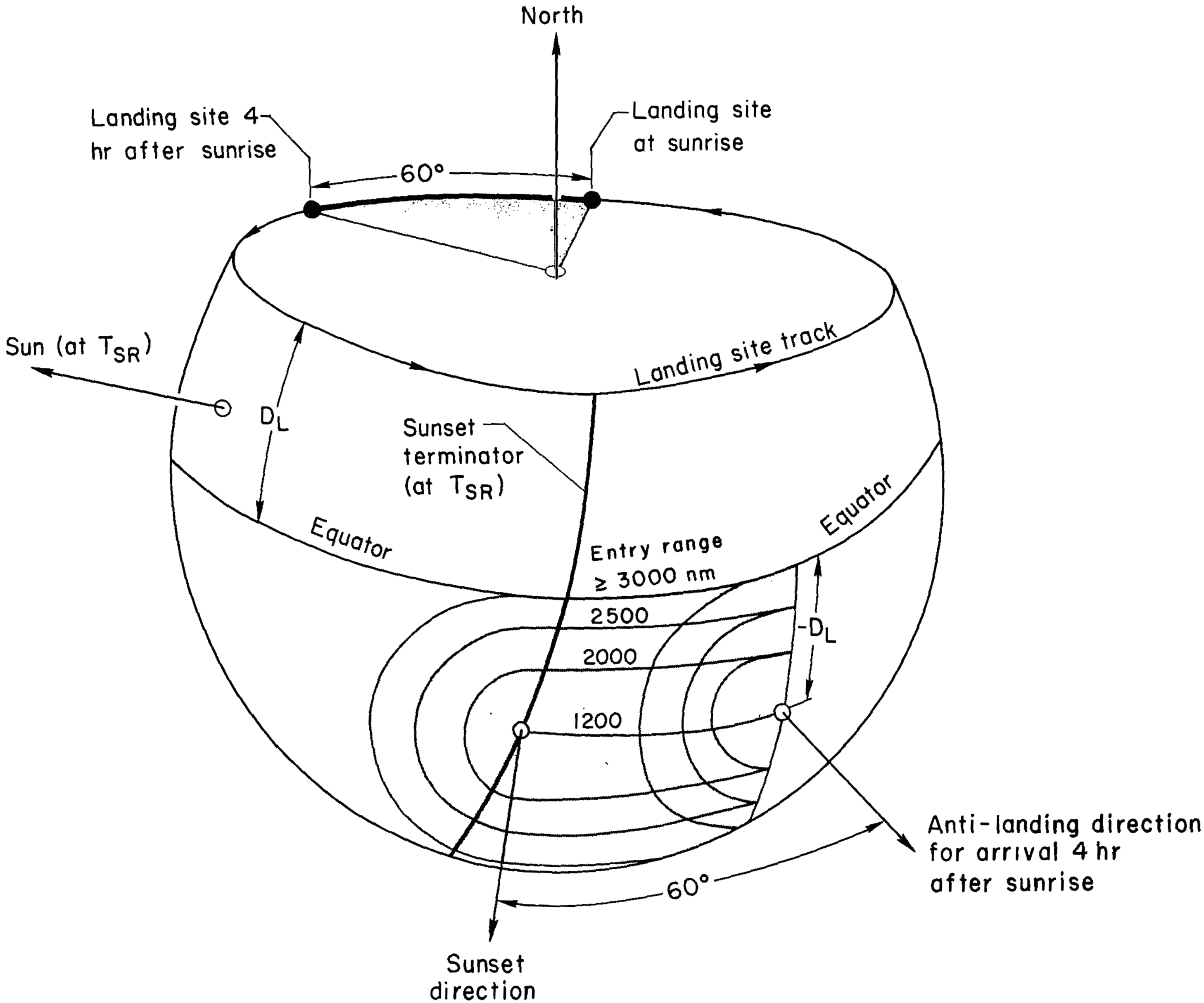
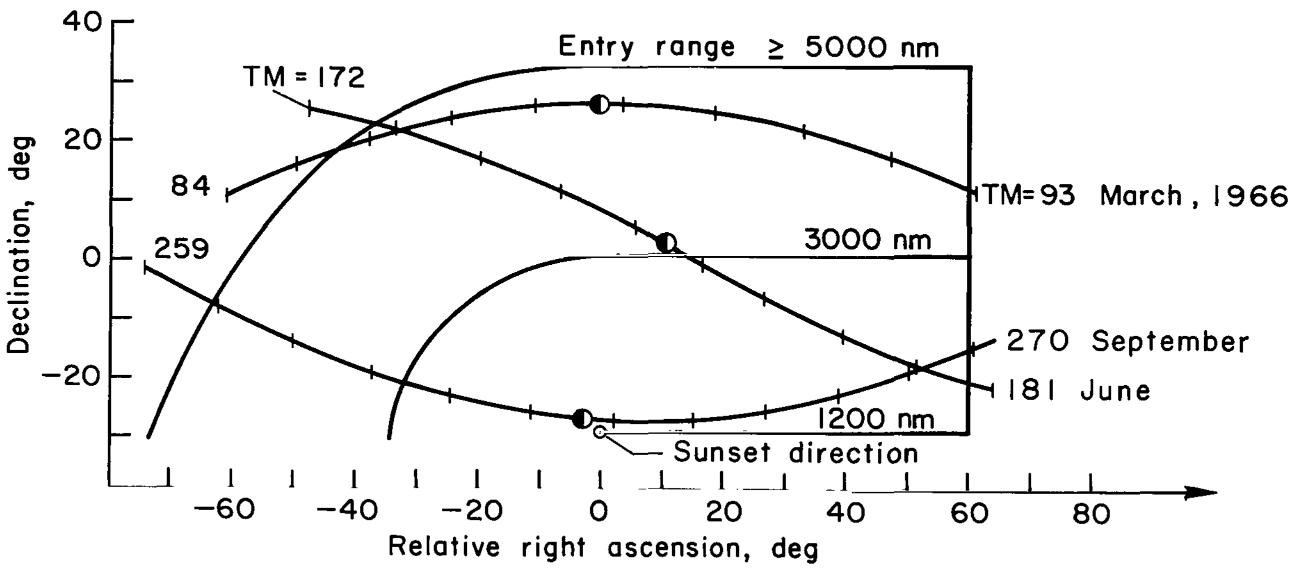
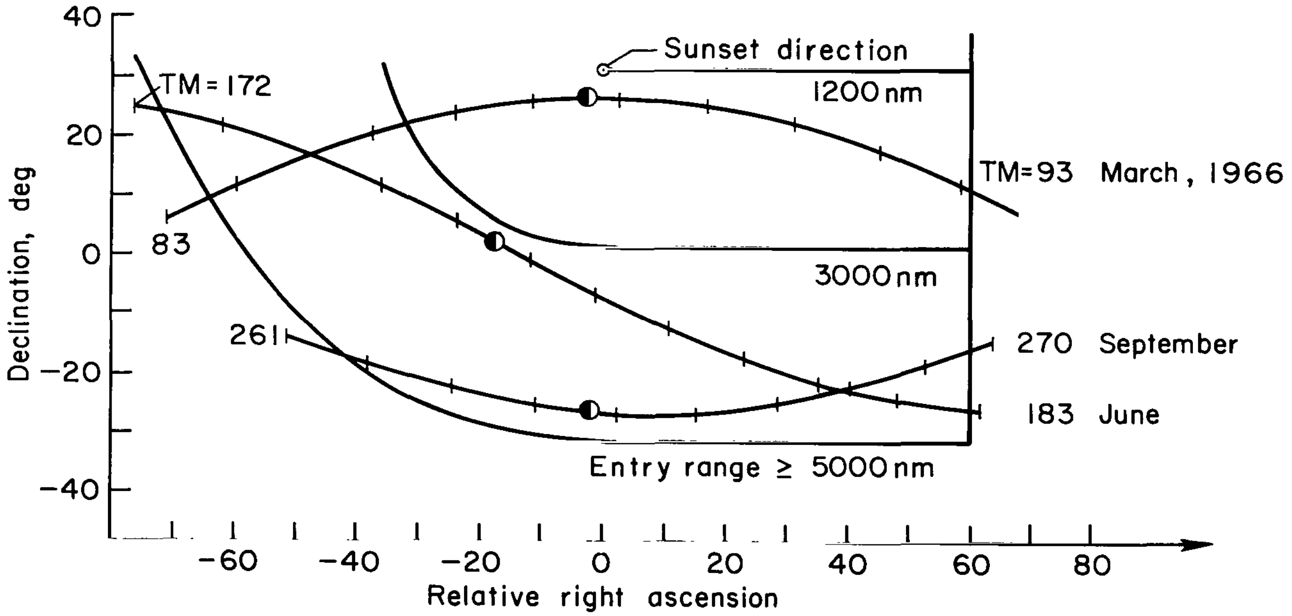


Figure 3.- Required launch region on the celestial sphere for early daylight landing.

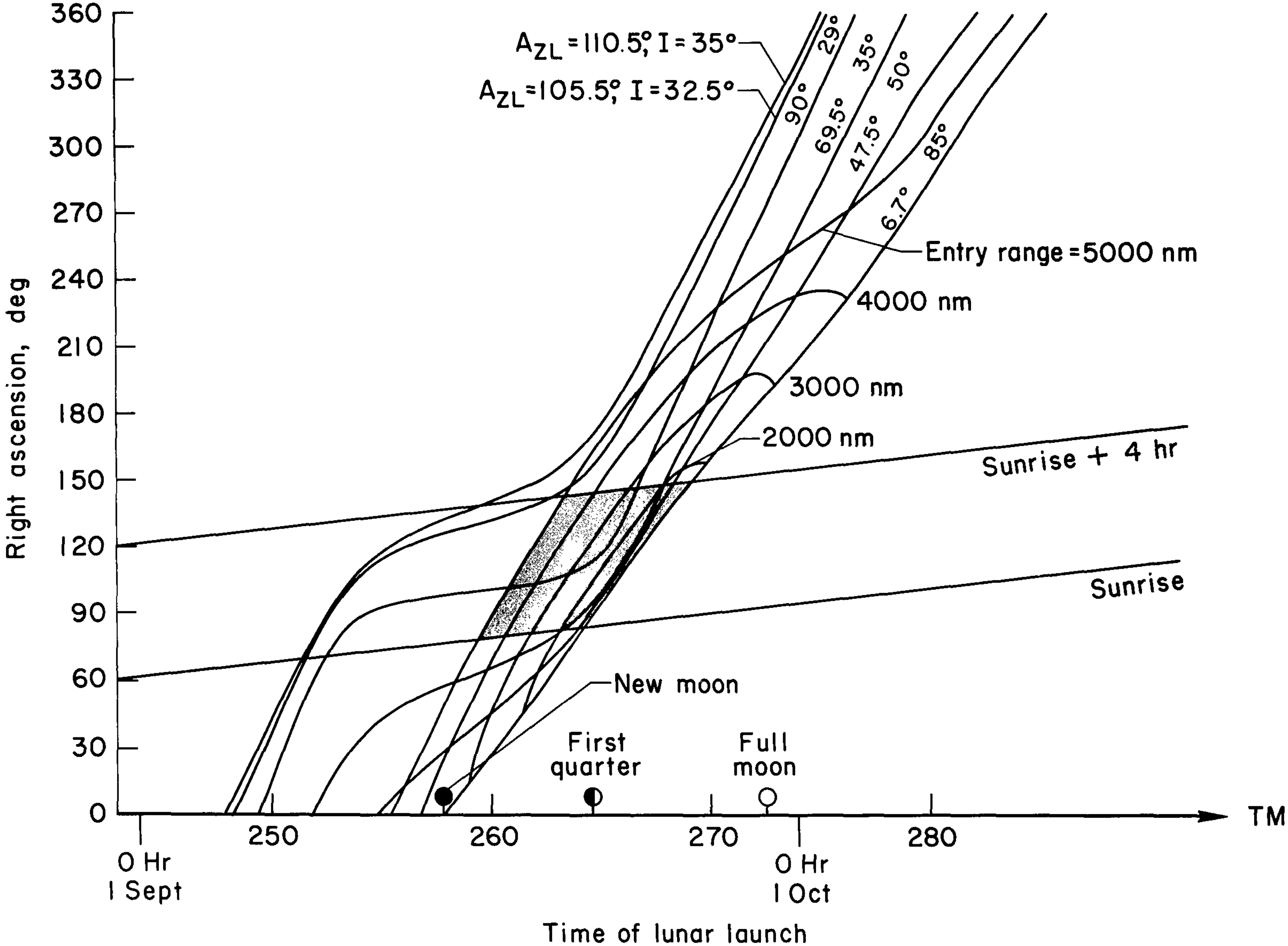


(a) Landing-site latitude 29° N.



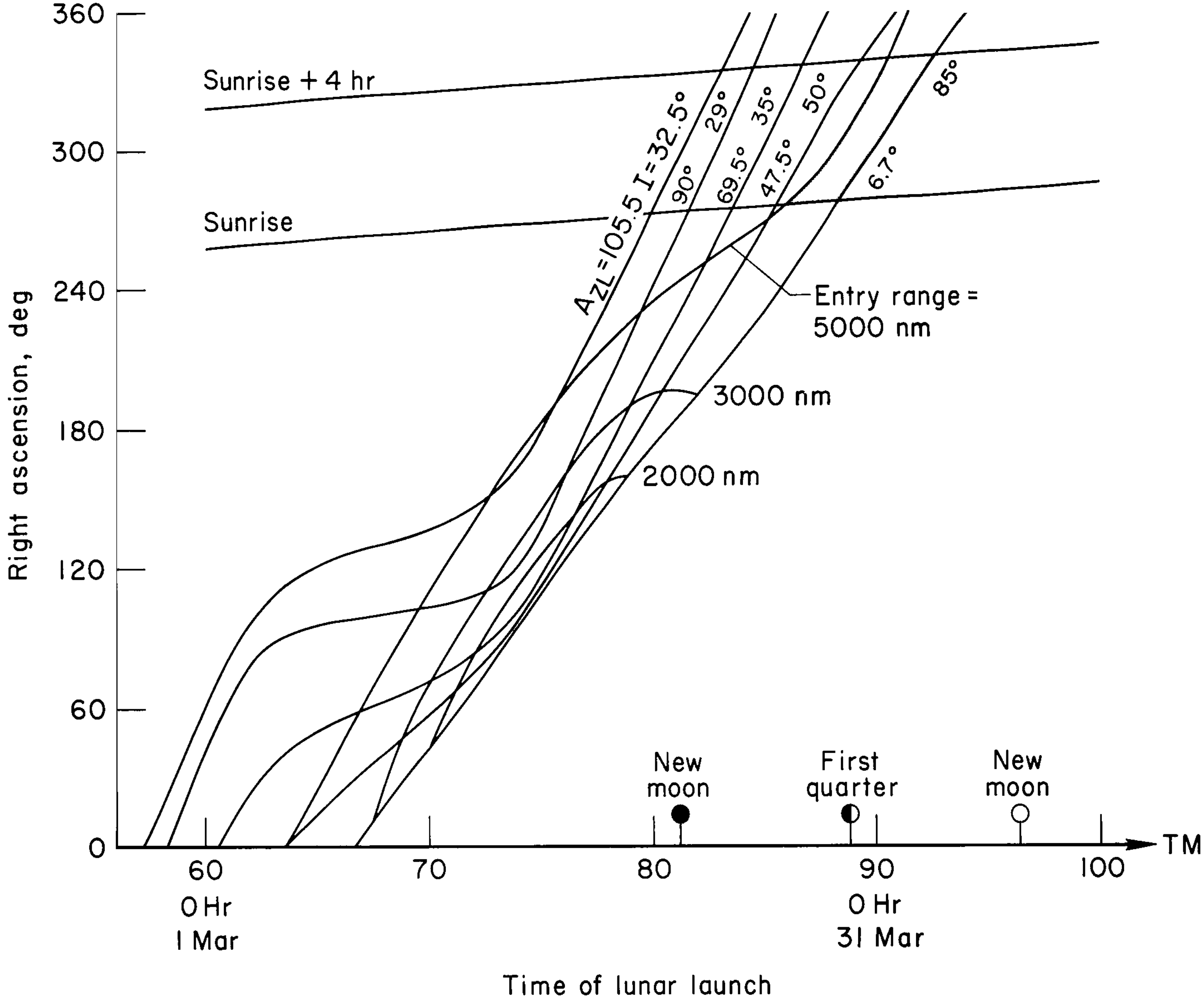
(b) Landing-site latitude 31.4° S.

Figure 4.- Moon's passage through launch region for early daylight landing.



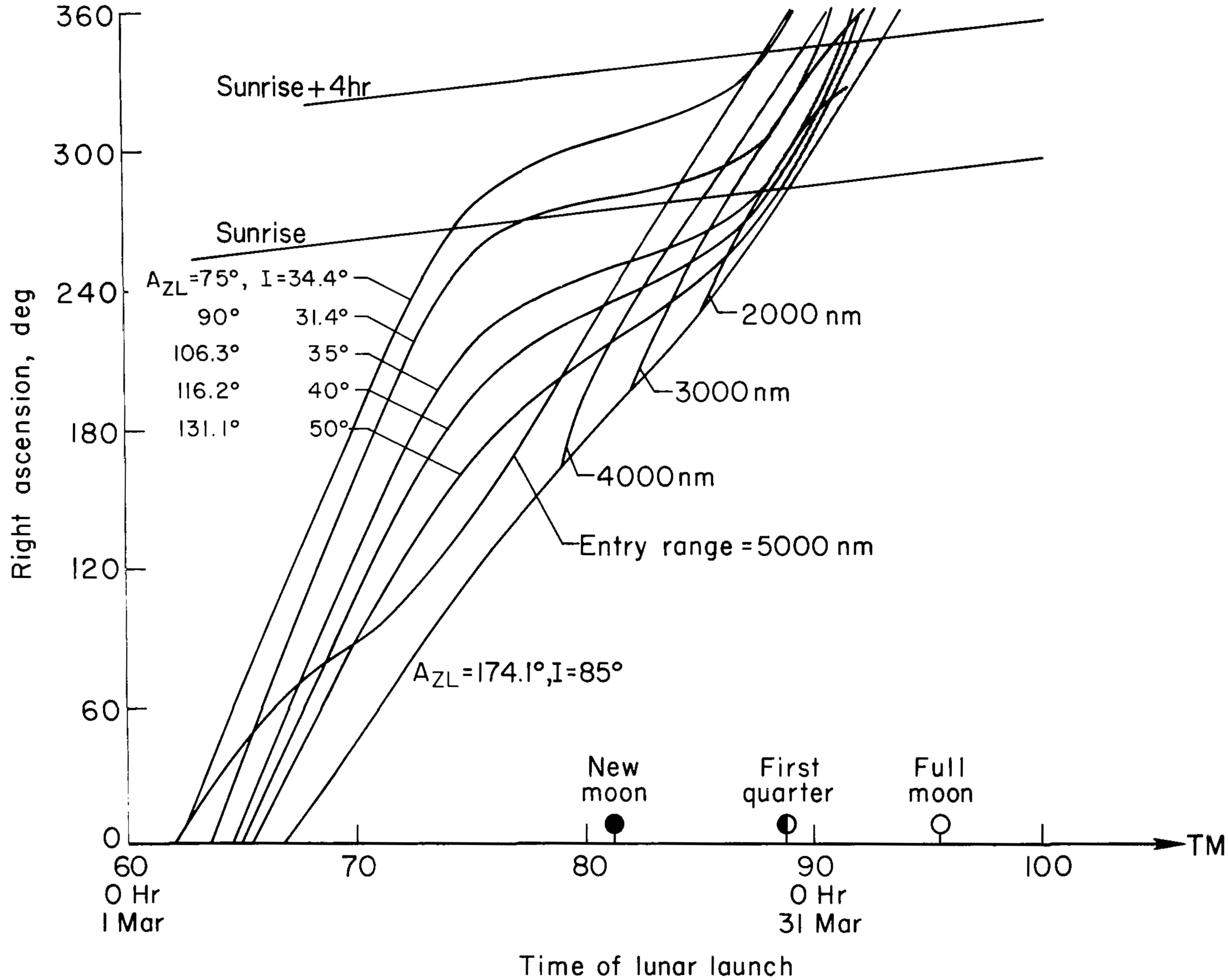
(a) Landing site: San Antonio, Sept.-Oct. 1966.

Figure 5.- Right ascension at landing vs. time of launch from the Moon.



(b) Landing site: San Antonio, Mar.-April 1966.

Figure 5.- Continued.



(c) Landing site: Woomera, Australia, March-April 1966.

Figure 5.- Concluded.

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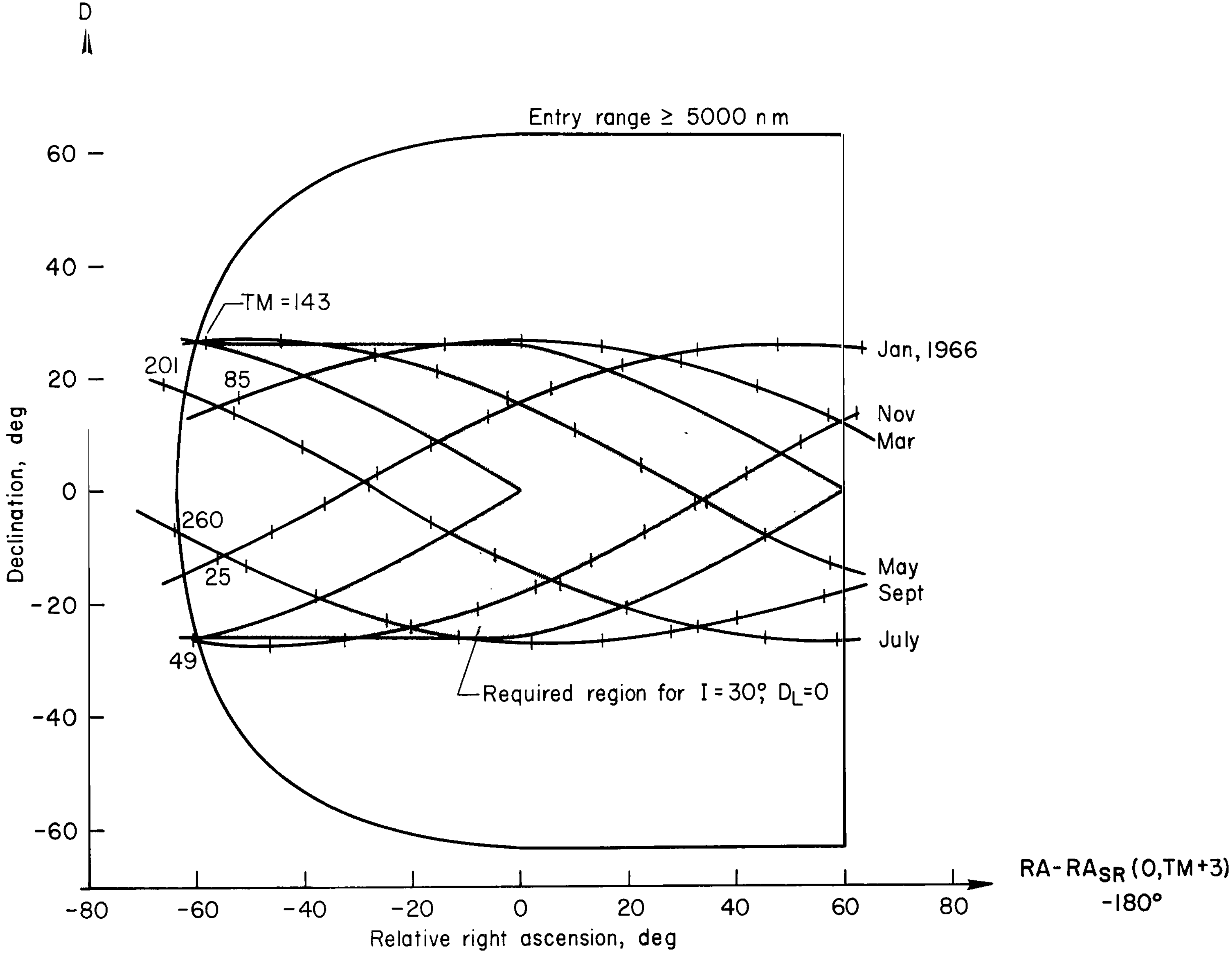

Figure 6.- Passage of the moon through the required region of the sky; 1966 - equatorial landing site.